

ULTRA-LOW-NOISE, InP FIELD EFFECT TRANSISTOR AMPLIFIERS FOR RADIO ASTRONOMY RECEIVERS

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ABSTRACT—Recent developments in ultra-low-noise, cryogenically-cooled, heterostructure field effect transistor (HFET's) microwave integrated circuit (MIC) amplifiers for frequencies up to 118 GHz are reviewed. Design and examples of the realization of InP HFET amplifiers and receivers in the frequency range 3 to 118 GHz are described. Applications to ultra-low-noise radio astronomy receivers, as well as broadband continuum radiometers, are discussed.

INTRODUCTION

In the early 1970's, the ultra-low-noise receiving systems employed mainly solid-state masers, cryogenically-cooled parametric amplifiers (or converters) and Schottky diode mixers. At the end of that decade, the advances in the technology of GaAs FET's, combined with cryogenic cooling, made the noise performance of GaAs FET amplifiers competitive with the performance of parametric amplifiers [1]. Progress in the noise performance of FET and HFET amplifiers at cryogenic temperatures was quite dramatic. In 1980, a noise temperature of 20 K at the frequency of 4.75 GHz was measured at the physical temperature of 18 K for a GaAs field effect transistor (FET) having .7 μm long gate [1]. In 1993, under similar conditions, the noise temperature of 15 K was measured at the frequency of 43 GHz [2] for an InP lattice-matched heterostructure FET having .1 μm long gate. This progress has been achieved by addressing two issues in FET (HFET) design: (1) maximization of intrinsic cut-off frequency $f_T = g_m/2\pi C_{gs}$, where g_m and C_{gs} are transconductance and gate capacitance, respectively, and (2) minimization of parasitic resistances of gate and source, r_g and r_s , respectively. The first issue was addressed by an advancement in the technology of artificially structured semiconductors on which the FET structures are built and the progress in the definition and fabrication of submicrometer length gates [3]. The epitaxial GaAs material used exclusively for low-noise FET fabrication in the 1970's was replaced by progressively more complex heterostructures: AlGaAs/GaAs, AlGaAs/InGaAs/GaAs, and AlInAs/GaInAs/InP. The second issue was addressed by the improvements in FET layout, fabrication of "mushroom" or T-shaped gates, reduction in drain-to-source separation and progress in the technology of the ohmic contacts [3]. The quantitative influence of these parameters can be quite accurately determined from the noise model developed by Pospieszalski [4] which gives the following approximate expression for the minimum noise temperature of a FET chip:

$$T_{\min} = 2 \frac{f}{f_T} \sqrt{r_t T_g g_{ds} T_d} \quad (1)$$

where T_{\min} is the minimum noise temperature, f is frequency, f_T is the intrinsic cut-off frequency $f_T = g_m/2\pi C_{gs}$, T_g and T_d are equivalent gate and drain temperatures, respectively; g_{ds} is the drain-to-source conductance; and $r_t = r_s + r_g + r_{gs}$, where r_{gs} is the intrinsic gate resistance. Most experiments show T_g to be approximately equal to the physical temperature T_a of a device [2], [4], [8], [10], [11], [13], [14]. For the range of useful operating biases, the equivalent drain temperature is approximately a linear function of drain current density per unit gate width. Also, for a given current density, it does not depend strongly on the device ambient temperature.

Since 1993, progress in the noise performance has not been significant. However, the technology of InP devices has matured and allowed for system insertion. The hybrid "chip and wire" amplifiers have been demonstrated up to frequencies of 118 GHz and successfully used in several instruments for radio astronomy research. These include: Very Large Array (VLA), Very Large Baseline Array (VLBA), Green Bank Telescope (GBT), Microwave Anisotropy Probe (MAP) and several ground-based instruments for the investigation of cosmic microwave background. A number of MMIC designs were demonstrated at room temperature up to 190 GHz (for example, [5], [6]) and up to 115 GHz for cryogenic applications [7]. In radio astronomy instrumentation, HFET receivers now compete in performance with masers and SIS mixer/HFET IF amplifier tandems for frequencies below 120 GHz. At frequencies above 120 GHz up to about 1 THz, SIS mixers demonstrate the best noise performance. Above 1 THz, cooled Schottky diode mixers and hot electron bolometer (HEB) mixers provide the lowest noise temperatures.

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LOW-NOISE HFET AMPLIFIERS: STATE-OF-THE-ART

The NRAO Central Development Laboratory has developed a number of InP HFET millimeter-wave amplifiers in the 3 to 118 GHz range for applications in radio astronomy receiving systems [2], [8]-[12]. Very interesting results, especially at lower frequencies, have also been published by other laboratories [13], [14].

A summary of noise performance of HFET receivers cooled to approximately 20 K and a comparison with typical performance of SIS mixer receivers cooled to 4 K is presented in Fig. 1. Fig. 1 also shows the best performance of InP HFET receivers expected at any frequency for current state-of-the-art devices. This graph is based on minimum noise measure of a state-of-the-art, .1 μm gate length InP HFET and includes a modest correction to the receiver noise temperature estimated from typical losses of matching circuits, waveguides, horns, and dewar windows. The minimum noise measure is equal to the minimum noise temperature of an amplifier with the infinite number of stages, each stage with the optimal embedding circuit. Therefore, it establishes a limit of noise performance for a receiver in which an amplifier has sufficient gain to make contribution of subsequent mixer and/or amplifiers insignificant. A broadband HFET amplifier design can attain the noise temperature equal to the minimum noise measure only at discrete frequencies, a property clearly illustrated in Fig. 1. The examples of HFET receiver noise temperature, shown in Fig. 1, demonstrate that for a typical rectangular waveguide bandwidth, the average noise temperature is approximately equal to the value determined by the minimum noise measure at the highest frequency within the band.

The detailed characteristics of many of the amplifiers used in the construction of the laboratory receivers of Fig. 1 will be discussed during presentation. Fig. 2 shows examples of noise and gain performance of wide band 3-13 GHz and 8-18 GHz amplifiers, each having a total power dissipation of about 7 mW. An example of noise performance of a wide band laboratory receiver covering 68-118 GHz is shown in Fig. 3. The amplifier has gain > 30 dB using about 30 mW of power.

MIC amplifiers can be built to exhibit very repeatable characteristics, both with the relation to noise and complex gain. This is very important for broadband differential radiometers, as those employed in the Microwave Anisotropy Probe (MAP) mission [15]. The noise temperatures of about 120 amplifiers, covering different frequency bands, are shown in Fig. 4 for two physical temperatures, 297 K and 80 K. Finally, examples of gain repeatability of 40 W-band amplifiers and their phase tracking are shown in Figs. 5 and 6, respectively.

It is interesting to note that the noise model of [4], briefly discussed in the Introduction, correctly predicts the noise temperature over the whole 20 K to 300 K range of physical temperatures. A comparison between the measured and predicted gain and noise characteristics at room temperature for a MAP W-band amplifier is shown in Fig. 7. A comparison of the same characteristics measured at cryogenic temperatures is shown in Fig. 8.

DISCUSSION

It is interesting to observe that the graph of expected noise temperature of InP HFET receivers shown in Fig. 1 was first published in 1992 [16]. In subsequent years, it has been "validated" by a number of receiver realizations. However, since 1992, progress in the noise performance of devices has not been significant. The technology of low-noise InP HFET's matured in this period but no "next generation" low-noise HFET device emerged. At first, it seems surprising, given the extremely rapid developments of the 1980's, when three generations of new structures, AlGaAs/GaAs, AlGaAs/GaInAs/GaAs and AlInAs/GaInAs/InP, have been developed. But presently, the noise temperature of InP HFET receivers at the frequencies of commercial and military applications does not constitute a dominant part of a system noise for terrestrial systems, even those operating at room temperature. This, in turn, led to the significant reduction of funding for research on new structures, in favor of improvement in manufacturing procedures and the development of MMIC's. All of the results of Fig. 1, establishing the current state-of-the-art, have been achieved using MIC "chip and wire" technology. At W-band frequencies, similar or better results using MMIC's have already been demonstrated [7], while at other frequencies this is to be expected in the not-to-distant future.

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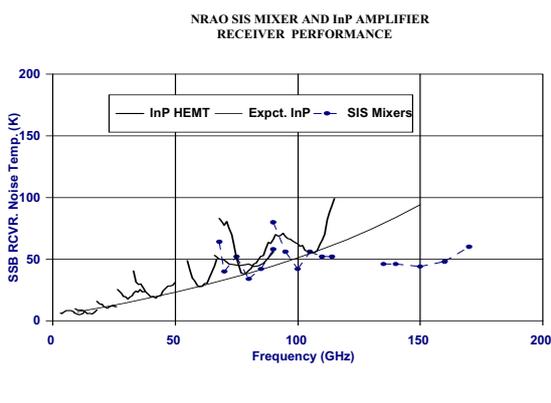


Fig. 1. Comparison of noise temperature of NRAO cryogenic receivers using InP HEMT amplifiers cooled to about 20 K and SIS mixer receivers cooled to 4 K (SIS mixer receiver data courtesy of A. R. Kerr and S.-K. Pan, NRAO).

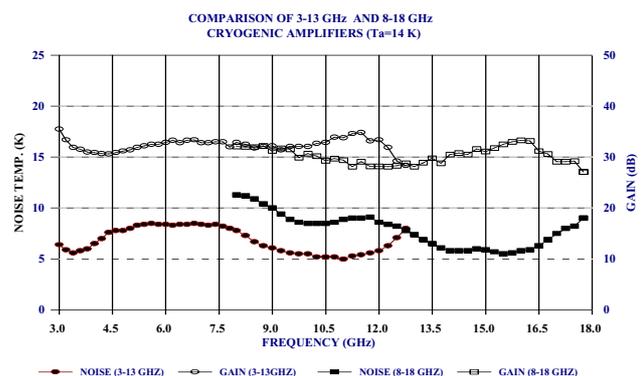


Fig. 2. Example of cryogenic performance of 3-13 and 8-18 GHz amplifiers using InP HFET's. For both amplifiers, the total power dissipation is 7 mW.

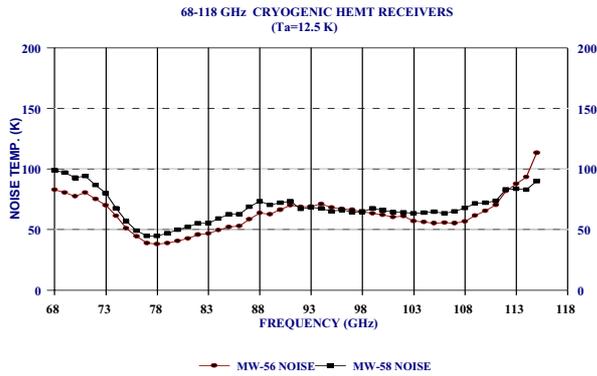


Fig. 3. Examples of noise performance of 68-118 GHz laboratory receiver.

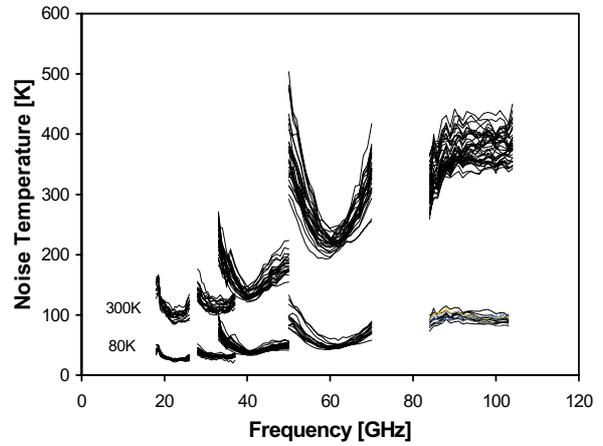


Fig. 4. Measured noise performance of all MAP amplifiers at room temperature and 80 K.

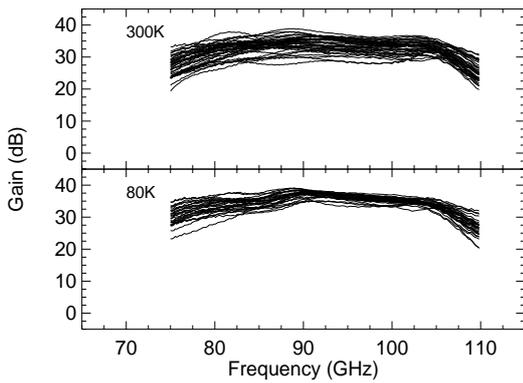


Fig. 5. Measured gain performance of 40 W-band amplifiers.

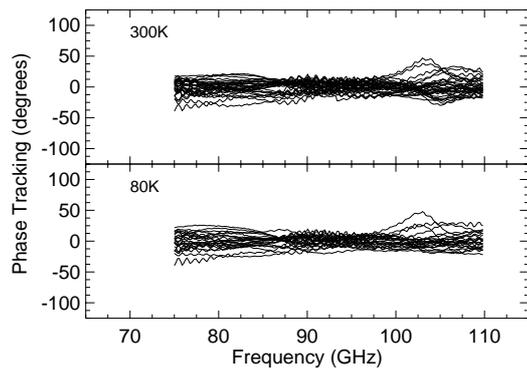


Fig. 6. Phase tracking of 30 W-band amplifiers at 300 K and 23 W-band amplifiers at 80 K.

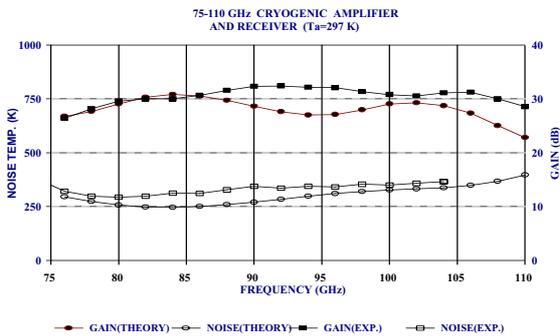


Fig. 7. A comparison of measured gain and noise characteristics of a W-band amplifier with model prediction at room temperature. Measured noise includes the contribution of pyramidal horn and receiver ($T_n \approx 2000$ K).

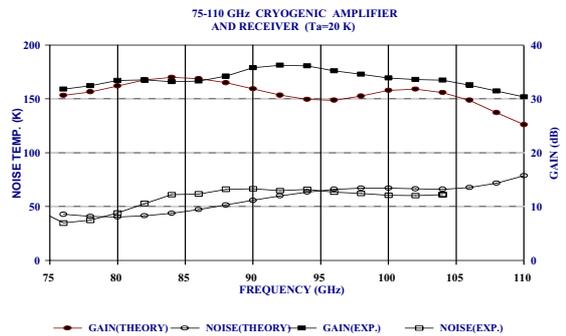


Fig. 8. A comparison of measured gain and noise characteristics of a W-band amplifier with model prediction at cryogenic temperature ($T_a = 20$ K). Measured noise temperature includes the contribution of dewar window, pyramidal horn ($T_a = 20$ K) and room temperature receiver ($T_n \approx 2000$ K).